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14. ABSTRACT In this paper we present initial experimental results of our ongoing development of a family of high Q-factor inplane microelectromechanical systems (MEMS) seismic sensors. Devices have been constructed that demonstrate all the required components of a MEMS seismic sensor, these include 11.5-Hz, high “Q”, silicon spring mass systems, multiple electro-magnetic actuators integrated onto the proof mass, and a highly accurate displacement transducer based on our Linear Capacitive Array Transducer (LCAT). The performance of each of these elements is discussed in the paper. The difficulties encountered in the assembly of these devices and the progress in transferring this technology to a commercial MEMS fabrication is also discussed. The result of a separate study on the potential use of these devices in high shock conditions is also presented. The devices have been integrated with electronics, both to characterize the performance of the individual sensor elements but also to complete the overall system by providing force feedback to the sensor die to form a force-feedback sensor. We present our initial results on using simple proportional feedback electronics with the device to form a force-feedback accelerometer and show that the performance is closely simulated by our theoretical models.					
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**INITIAL RESULTS ON RUGGED LOW POWER COMPACT SILICON MEMS SENSORS FOR USE IN
NUCLEAR EXPLOSION MONITORING**

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Sponsored by Air Force Research Laboratory

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ABSTRACT

In this paper we present initial experimental results of our ongoing development of a family of high Q-factor in-plane microelectromechanical systems (MEMS) seismic sensors. Devices have been constructed that demonstrate all the required components of a MEMS seismic sensor, these include 11.5-Hz, high "Q", silicon spring mass systems, multiple electro-magnetic actuators integrated onto the proof mass, and a highly accurate displacement transducer based on our Linear Capacitive Array Transducer (LCAT). The performance of each of these elements is discussed in the paper. The difficulties encountered in the assembly of these devices and the progress in transferring this technology to a commercial MEMS fabrication is also discussed. The result of a separate study on the potential use of these devices in high shock conditions is also presented. The devices have been integrated with electronics, both to characterize the performance of the individual sensor elements but also to complete the overall system by providing force feedback to the sensor die to form a force-feedback sensor. We present our initial results on using simple proportional feedback electronics with the device to form a force-feedback accelerometer and show that the performance is closely simulated by our theoretical models.

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OBJECTIVES

The objective of this research program is to develop a silicon MEMS sensor suitable for use in Nuclear Explosion Monitoring Systems (NEMS). In Phase A we are developing a triaxial sensor model that we will fabricate and evaluate. This design would then be further optimized in Phase B of the development.

RESEARCH ACCOMPLISHED

Introduction

Our goal in Phase A of the project has been to complete the design and fabrication of the MEMS component of the sensor optimized for NEMS applications. The MEMS sensor integrates the proof mass and its suspension (Pike and Kumar, 2007), a displacement transducer, and a set of electromagnetic transducer coils.

To produce a working microseismometer (μSeis) this MEMS element is coupled with electronic circuitry that excites the displacement transducer, amplifies and demodulates the displacement signal, and then feeds back the correct signal to the coils to cause the device to operate as a force-balance acceleration or velocity sensor. Finally, both the MEMS elements and the associated electronics have to be held in a suitable mechanical package to allow the device to operate under field conditions.

For sensing Nuclear Explosions it has been suggested that the noise performance of $\sim 1 \text{ nano-g}/\sqrt{\text{Hz}}$ in the band from 10 Hz to 40 Hz is of considerable interest. These are the design levels used for the micro-seismometer (Standley & Pike 2007).

Device Design Parameters

In this phase of the development, we have concentrated on the performance of a device based on a 20-mm x 20-mm die size and a natural frequency of 11.5 Hz sealed at ambient pressure with a Q-factor of approximately 275. This device includes enhancements to improve the shock resistance, and the same basic device structure was fabricated at both Imperial College and Innovative Micro Technology (IMT). This device uses a 200-micron period for the displacement transducer and assumes a spacing of the DT wafer of ~ 38 microns when sealed at ambient pressure. The design parameters are summarized in Table 1.

Table 1. Device Design Parameters.

Device	Proof Mass Die Dimensions	Resonant Frequency/Hz	Q-Factor	Environment	DT Period / μm	Shock Resistance
11.5-Hz Device	20mm x 20mm x 0.5mm	11.5 Hz	275	Ambient Pressure	200	Moderate

In this paper we are reporting on devices fabricated at Imperial College that used a simpler geometry on the displacement transducer die which results in higher damping and a lower "Q". These devices were also not sealed. These changes were made for the initial devices to allow easier fabrication. Four devices have been fabricated and two have been evaluated.

Measured Device Parameters

Two devices have been characterized and the results are presented in Table 2 below. The performance of the spring mass system was in excellent agreement with the design theory and the resonant frequency was within $\pm 5\%$ of the design value. Figure 1 shows the open loop transfer function of Die 5 when it was driven by the calibration coil, the resonance can be clearly seen, and also the first spurious resonance which occurs at ~ 100 Hz. The first spurious mode is due to the finite mass of the suspension itself, which was minimized in this design, and predicted to occur at ~ 110 Hz (Pike and Standley, 2005, and Pike and Kumar, 2007).

Table 2: Measured Device Parameters

Parameter	Die 4	Die 5	Target	Units	Comment
Resonant Frequency	11.5	11.125	11.5	Hz	Measured
Device "Q"	63	40	275		Design Change
Mass	0.229	0.229	0.245	grams	Design Value
Motion 1g	1.877	2.006	1.878	mm	Calculated
Gain DT Mechanical	38280	63360	71760	V/m	Separation Dependent
Sensitivity Open Loop	71.85	127.08		V/g	Calculated
Main Coil Resistance	1100	1128	698	Ohms	Measured
Main Coil Generator Const	0.412	0.394	0.433	N/Amp	Calculated
Integral Coil Resistance	Open	1046	771	Ohms	Measured
Integral Coil Generator Const	Open	0.426	0.472	N/Amp	Calculated
Calibration Coil Resistance	630	Open	260	Ohms	Measured
Cal Coil Generator Const	0.086	Open	0.144	N/Amp	Calculated

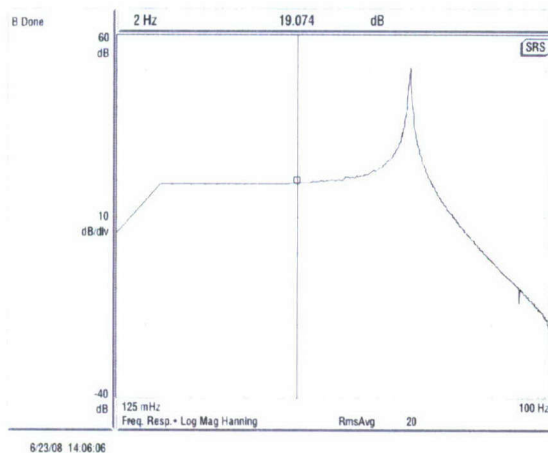


Figure 1: Die 5 Open Loop Response

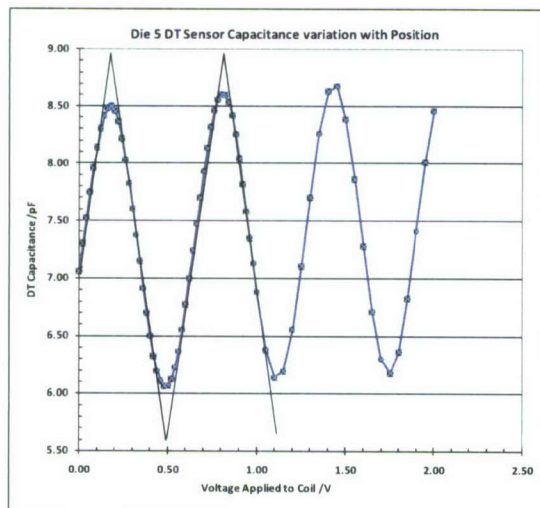


Figure 2: Displacement Transducer Capacitance

The device "Q" in this case is about 40 and is limited by the Couette damping of the flat displacement transducer plate. The spacing on this device is closer than the design value of 38 microns, partly explaining the lower value compared with Die 4. Die 4 had a "Q" of 63, while test devices fabricated with no metallization but with the relieved areas on the displacement transducer wafer show "Q" values of several hundred under ambient pressure, in good agreement with the theoretical model. Previously we have reported that in a vacuum "Q"s in excess of 100,000 are obtainable (Standley & Pike 2007).

The capacitance values of the displacement transducer on Die 5 were measured as the proof that mass was moved by passing current through the main coil. Figure 2 shows the variation of the sensor capacitance as the displacement transducer is moved by applying a voltage to the main coil on the proof mass with the magnets present. The results show a nominal sensing capacitance of 3.5pF superimposed on a stray capacitance of approximately 5.5pF. The design value was a 3.3pF sensing capacitor with approximately 2pF of stray capacitance. The additional strays are likely due to the connections and cabling used in the test setup.

The Displacement Transducer circuit was then connected to die 5, and the proof mass moved by applying a voltage to both the Main and Integral coils of the device. The results are shown in Figure 3 and demonstrate the operation of the LCAT. The mechanical sensitivity of the displacement transducer was approximately 63kV/m compared with the predicted value of 72V/m. As the separation between the proof mass and the

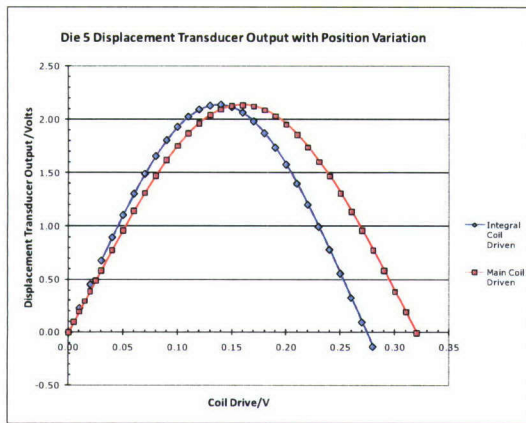


Figure 3: Displacement Transducer Output

constants are between 5-10% lower than the design values, some of this is due to variation of the magnetic components, while about 5% can be explained by a slightly higher than designed separation of the magnetic pole pieces to ensure that they do not touch the device. The coil resistances were higher than designed due to a higher sheet resistance of the electro-plated layer. Process improvements should reduce this resistance in future devices.

Die Packaging & Interconnection and Commercial Fabrication Results

We still have some fabrication and packaging challenges with the devices fabricated at Imperial. Firstly, our yield is still low on the proof mass fabrication stage. This is a result of the relatively complex process required to make the devices and in particular the two layer metallization. Recently, the yield has improved and a way of repairing metallization faults has been developed. In the long term we are confident that our commercial MEMS fabrication partner can solve the yield issues.

The other remaining problems at the chip level concern the packaging. We have developed a process that allows us to electrically interconnect the proof mass wafer to the displacement transducer wafer and to control the spacing between the two wafers. We have not yet succeeded in sealing the three-wafer stack to isolate the devices from the surrounding atmosphere, we also are working on finding a better technology to machine the glass wafers so the cavities can be machined with good positional accuracy across a whole wafer. These tasks will be the focus of a later fabrication run.

Our commercial MEMS partner (IMT) demonstrated all the essential elements of fabricating the proof mass including the following:

- Substrate Contact
- First Metal Layer
- High Temperature Insulator
- Second Electroplated Metal Layer
- DRIE etching of the proof mass and production of high “Q” spring mass systems

The yield on the initial wafer was low, but process and mask changes in the next phase should result in significant improvement.

The first wafer stack bonded at IMT cracked on the second bond and the cavity wafer delaminated from the proof mass and the DT. Also the spacing between the DT and the proof mass was too small so the proof masses could not move freely. Further process development is required to develop the frit bonding process, the vacuum gettering, and the wafer-to-wafer electrical interconnect.

Displacement Transducer in die 5 is probably below the nominal 38 microns, this suggests that the nominal mechanical sensitivity is $\sim 50\text{kV/m}$ for this design. This suggests that stray capacitance and fringing fields are higher than our theoretical model. The theoretical noise figure is still well within our design limits with a theoretical displacement noise floor of $\sim 0.225\text{picometers}/\sqrt{\text{Hz}}$.

With the Displacement Transducer functional and the proof mass parameters measured, the generator constants of the electro-magnetic actuators could be determined. As shown in Figure 3, a certain voltage level is required to move the proof mass through a half period of the LCAT or 100 microns in this design. Knowing this and the spring constant of the proof mass suspension gives the force exerted, using the coil resistance, determines the current necessary to oppose this force and from this the Generator Constants can be calculated. As can be seen in Table 1 the Generator

High Shock Testing

Seismometer suspensions are often exposed to high shock loading during transportation and deployment, particularly when utilized in drilling, automotive applications, space deployments, or military systems. High shock loading of suspensions can lead to failure due to fracture, delamination, or stiction. Additionally, for a suspension like that of the microseismometer, with a large range of travel and a low resonant frequency, the various components of the silicon suspension colliding with each other can lead to spallation damage and thus to a broken or severely compromised device. By completely embedding the suspension in a wax-like material which solidifies around the proof mass and springs, and thereby restrains them from motion, it should be possible to prevent any damage to these structures even in high shock environments. This encapsulating material would then be entirely removed via sublimation in order to return the suspension back to its original condition. Either heat or vacuum can be used to sublimate the encapsulant. To test this approach, impact trials of the suspension were carried out at a ballistic test range at Pendine in Wales. The impact velocity was about 310 m/s, impact angle between 88–108° creating a ‘tail slap’ with high in-plane acceleration. The in-axis peak acceleration was 20,000g at the front of the penetrator and around 10,000g at the rear of the penetrator. The lateral peak accelerations were measured at the rear of the penetrator and were 16,000g and 6,500g along the vertical and horizontal axes respectively. The compartment containing the suspensions was approximately in the middle of the penetrator. Suspensions were encapsulated within naphthalene and paradichlorobenzene (PDB) in a metal box. The sublimants were melted and poured into the boxes containing the suspensions. After the penetrator tests, these boxes were exposed to a 10^{-3} Torr vacuum, resulting in successful sublimation. Nine out of 12 suspensions that were encapsulated in naphthalene survived, as did 11 out of 12 suspensions that were encapsulated in PDB. In both cases, the sublimation was clean, resulting in suspensions with quality factors similar to those measured before the tests. This illustrates a potential method for protecting the silicon suspensions of the microseismometer against extremely high shocks prior to deployment.

Configuration as an Accelerometer

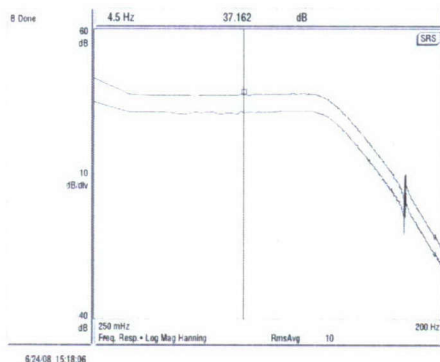


Figure 4. Accelerometer Transfer Function

The initial system testing of the device was performed by configuring the device as an accelerometer rather than a velocity sensor. This allowed initial evaluation of the performance of the device in a simple feedback circuit and allowed some other possible sources of error to be investigated before the more complex velocity feedback system is implemented. The device was configured as an accelerometer by driving the main coil from the displacement transducer through a resistor and capacitor in parallel. These two elements act as a proportional and differential feedback for the system. A 68nF capacitor was used in parallel to a 110k resistor. The output signal was taken from the top of the feedback resistor, passed through a unity gain buffer and then a final output stage that produced a differential output. The transfer function of the differential stage was actually unity due to the single ended to differential conversion scheme used. The circuit elements used were not optimized for this application as this topology was created by modifying a board designed to operate the device as a velocity sensor. The measured closed loop transfer function is shown in Figure 4. The measured sensitivity to acceleration was 40.3V/m/s^2 while PSPICE (Figure 5) predicted a slightly peaked response and a sensitivity of 42.4V/m/s^2 . This difference is only about 5% showing the model is a good predictor of circuit performance. The die and magnet assembly used in the tests is shown in Figure 6. The mounting assembly and electronics are shown in Figure 7. The device was installed in Kinemetrics vault as shown in Figure 8. The seismometer was co-located with an STS-2 shown in the top right of the picture. The package was aligned with the Galperin Axis of the sensor aligned to true north to coincide with the North axis of the STS-2. The device was connected to a Q330 with pre-amplifiers enabled, and an STS-2 was connected to the other channel group of the Q330, also with pre-amplifiers enabled to allow comparisons of the data. The device was thermally insulated with several layers of thermal blanketing and foam to reduce temperature effects. The device was found to be sensitive to the vault noise and the tilts registered on the STS-2's horizontal axis. As the device is on the Galperin axis, it responds to both horizontal and vertical noise. Without another device to remove the horizontal signal, the horizontal noise is expected to dominate the device performance in this vault.

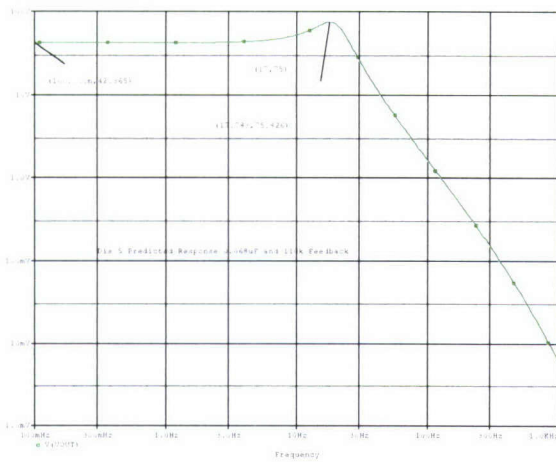


Figure 7: Predicted Accelerometer Response

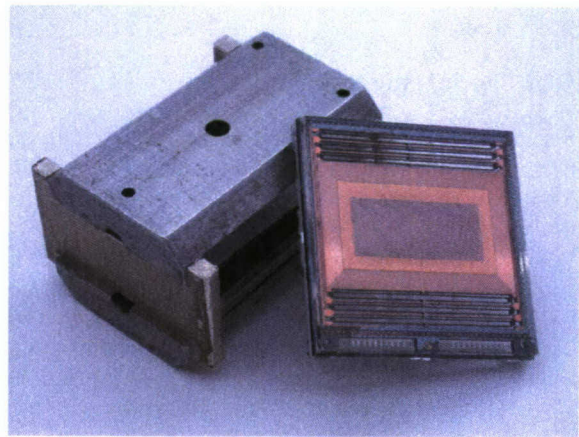


Figure 5: Die & Magnet Assembly

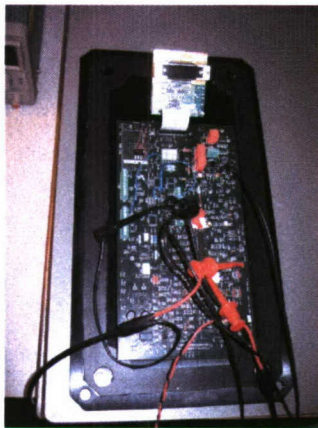


Figure 6: Device and Electronics



Figure 8: Unit installed in Vault

The device was run for over a week and several earthquakes were recorded. The noise analysis was performed on a 1.5 hour segment of data recorded in the late evening when no large seismic or other events were present and the cultural noise was at a minimum. The noise was processed in MatLab using a modified version of a United States Geologic Survey (USGS) Advanced National Seismic System program developed for accelerometer noise studies.

Figure 9 below shows typical vertical noise in the Kinometrics vault during quiet periods. As can be seen we will need to look at periods of longer than 10 seconds for the ambient noise to be below our design limit. Figures 10 and 11 show the analysis of 90 minutes of the 20 sps samples from the Q330. As can be seen, the noise reaches a minimum between 10 and 30 seconds of about 13 nano-g/ $\sqrt{\text{Hz}}$. This is currently considered to be an upper limit on the noise of the instrument. This is an order of magnitude higher than the design goal of < 1 nano-g/ $\sqrt{\text{Hz}}$ but already represents the lowest noise floor of a MEMS accelerometer presented to date.

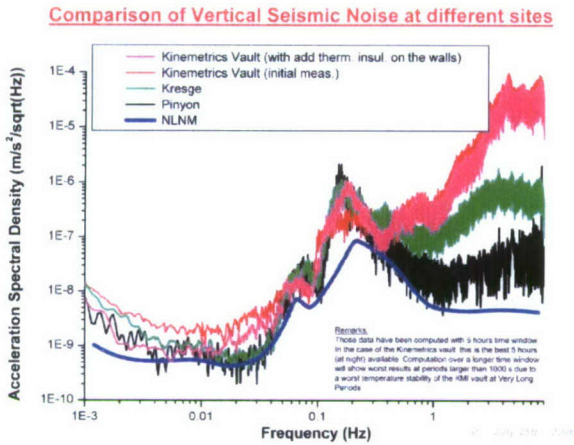


Figure 9. Vertical Noise in Kinemetrics Vault

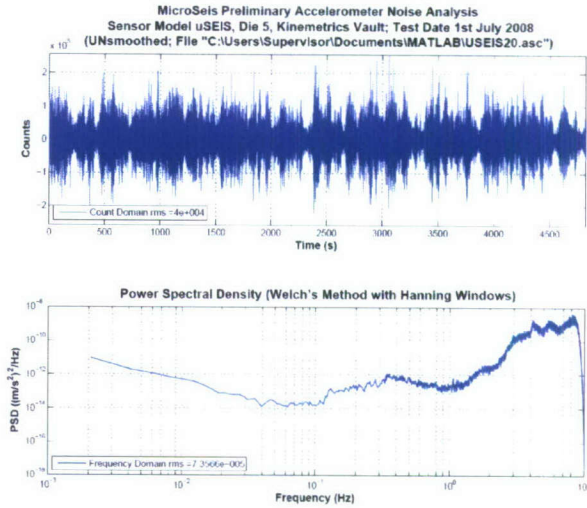


Figure 10. Time Series and PSD of 20 sps Data

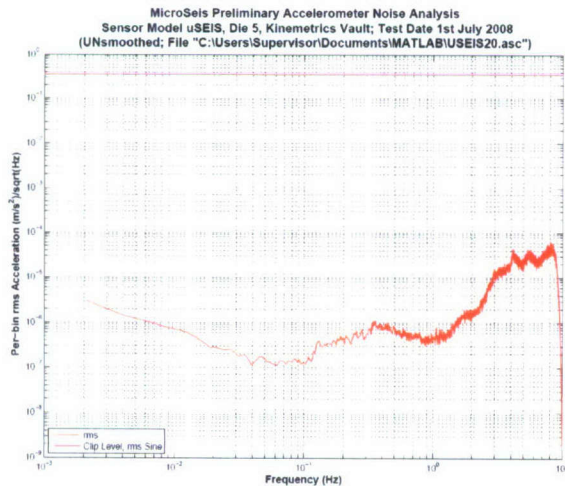


Figure 11. Acceleration Noise Floor

During the time the unit was in the vault it registered a magnitude 7.0 M_w earthquake east of the South Sandwich Islands on Monday June 30, 2008, at 06:17:43 UTC at 121 degrees from Pasadena. The event was recorded on the Q330 with pre-amplifiers enabled. In figure 12 we see the top trace is the micro-seismometer acceleration output. The three signals below are from the co-located STS-2 signals for the E, N, and Z directions. The micro-seismometer output should be a vector combination of the N and Z signal converted to acceleration. These data have been filtered by the LPWSS filter.

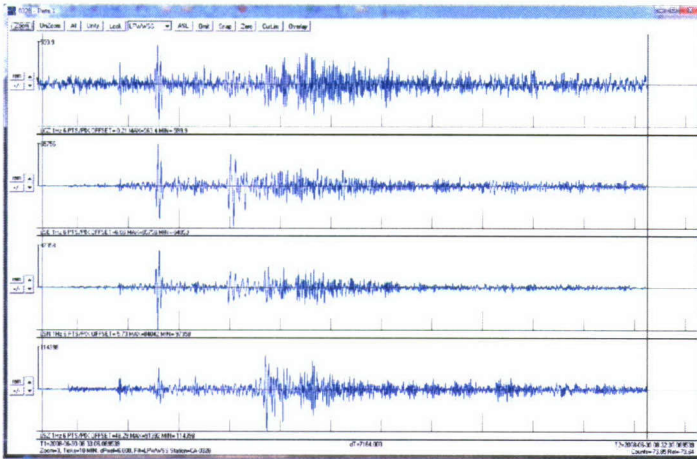


Figure 12. Magnitude 7.0 Mw Sandwich Island Quake

Further analysis was performed in MatLAB on the data. The data from the STS-2 was recombined to create a Galperin Axis pointed in the same direction as the Micro-seismometer. The acceleration data from the seismometer was then integrated to velocity and the results compared.

Figure 13 shows the data as a time series, Figure 14 shows the whole time series with the MEMS sensor data integrated compared to the calculated STS-2 U Axis. Figure 15 shows a small section on the same graph showing the correlation between the STS-2 and MEMS sensor data. This is an encouraging demonstration of the sensor performance.

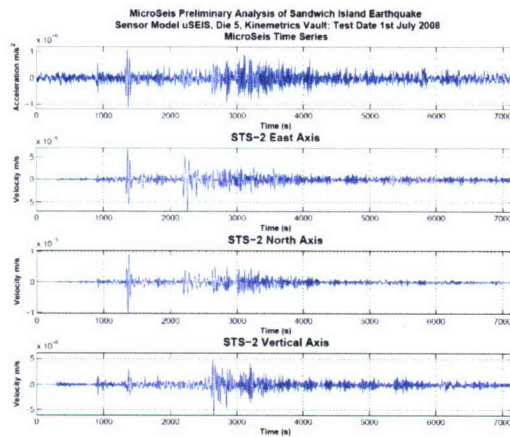


Figure 13. Time Series of Event

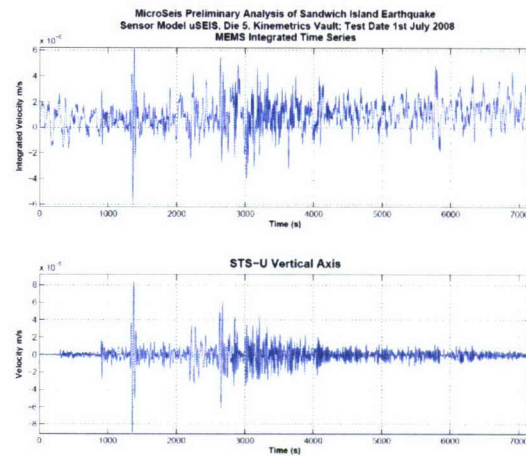


Figure 14. Comparison of MEMS output converted to velocity to STS-2 Composite Axis

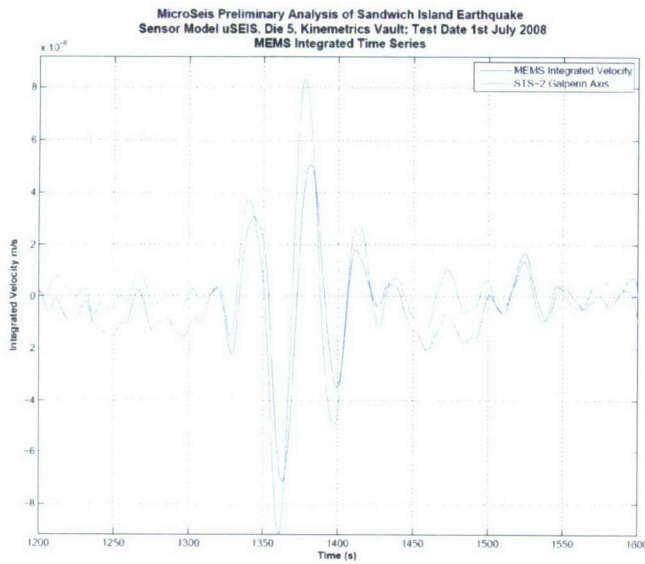


Figure 15. Comparison of seven minute section

Temperature Sensitivity

Figure 16 shows a one day segment of data from the micro seismometer correlated with the temperature of the vault slab. This indicates that the offset is caused by temperature and amounts to about $375 \mu\text{g}/^\circ\text{C}$ or about $650 \text{ ppm}/^\circ\text{C}$ of the gravity bias this is more than the expected $110 \text{ ppm}/^\circ\text{C}$. Further modeling suggests that this is composed of both an exaggerated temperature sensitivity about four times higher than predicted coupled with a long term temperature independent drift. This temperature sensitivity will be investigated further as it both causes long term drift but is also likely to be responsible for the $1/f$ noise of the sensor being elevated at lower frequencies.

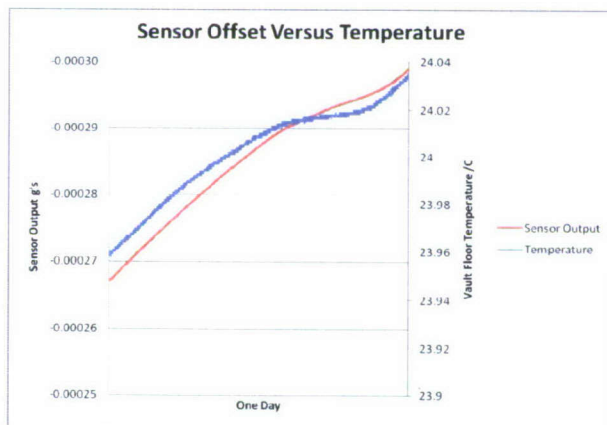


Figure 16. Sensor Offset & Vault Temperature

CONCLUSIONS AND RECOMMENDATIONS

These tests have shown that we have produced all the necessary components of a broad-band seismometer on our silicon die. Only the “Q” differs significantly from the design target and this will be improved in future device lots when an etched displacement die will be used.

A commercial process to produce the proof mass wafers has been demonstrated, but more work is required to improve the yield and also to develop the vacuum sealing techniques for the wafer stack.

An overall packaging technique has been demonstrated that provides the electrical connections and required separation for device operation. The device has been integrated with simple feedback electronics and a demonstrated noise performance of ~ 13 nano-g/ $\sqrt{\text{Hz}}$. It has also recorded several earthquakes with moderate fidelity.

The next stage will be to evaluate the performance of the device as a velocity sensor. The next phase of the development will utilize the lessons learned from this testing to improve device performance and yield. It is recommended that the next phase of the development at the commercial MEMS facility should also be undertaken at this time.

In conclusion, we believe we have made substantial progress in the development of a MEMS sensor for use by the Nuclear Explosion Monitoring community.

ACKNOWLEDGEMENTS

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